

Spatiotemporal changes in water, land use, and ecosystem services in Central Asia considering climate changes and human activities

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Abstract: Central Asia is located in the hinterland of Eurasia, comprising Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan; over 93.00% of the total area is dryland. Temperature rise and human activities have severe impacts on the fragile ecosystems. Since the 1970s, nearly half the great lakes in Central Asia have shrunk and rivers are drying rapidly owing to climate changes and human activities. Water shortage and ecological crisis have attracted extensive international attention. In general, ecosystem services in Central Asia are declining, particularly with respect to biodiversity, water, and soil conservation. Furthermore, the annual average temperature and annual precipitation in Central Asia increased by 0.30°C/decade and 6.9 mm/decade in recent decades, respectively. Temperature rise significantly affected glacier retreat in the Tianshan Mountains and Pamir Mountains, which may intensify water shortage in the 21st century. The increase in precipitation cannot counterbalance the aggravation of water shortage caused by the temperature rise and human activities in Central Asia. The population of Central Asia is growing gradually, and its economy is increasing steadily. Moreover, the agricultural land has not been expended in the last two decades. Thus, water and ecological crises, such as the Aral Sea shrinkage in the 21st century, cannot be attributed to agriculture extension any longer. Unbalanced regional development and water interception/transfer have led to the irrational exploitation of water resources in some watersheds, inducing downstream water shortage and ecological degradation. In addition, accelerated industrialization and urbanization have intensified this process. Therefore, all Central Asian countries must urgently reach a consensus and adopt common measures for water and ecological protection.

Keywords: water resources; land-use changes; ecosystem services; climate changes; human activities; Aral Sea

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1 Introduction

Water resources, land use, and ecosystem services are crucial factors determining the quality of sustainable development in arid lands. These factors are often influenced by climate changes and human activities. Central Asia, which is in the hinterland of Eurasia, has one of the world's most sensitive and vulnerable ecosystems. This mountain–oasis–desert ecosystem has global importance, and above 93.00% of the total area is dryland. Central Asia is one of most water scarce regions in the world and shows the highest per capita water consumption. The vulnerability of water resources in this region has become increasingly prominent recently, and water resources are an important factor restricting this region's socioeconomic development (Yu et al., 2020). The Aral Sea crisis is a typical example of the human-induced environmental problem, necessitating more detailed research and management actions.

Central Asia comprises five nations: Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan. Because the region is a hinterland, moisture flow is difficult. Most areas are arid lands with rare precipitation and wicked environment. The annual temperature range is large, and the climate shows considerable continental characteristics. A previous study has shown that the annual mean temperature increased at an average rate of 0.30°C per decade from the 1960s to the 2000s and even faster in the 21st century (Yu et al., 2020). The terrain is complex and diverse, making it one of the world's most sensitive areas to climate changes (Lioubimtseva and Henebry, 2009). Based on remote sensing analysis, the total area of great lakes in Central Asia has reportedly reduced by 49.62% in the past decades (Bai et al., 2011). Rivers are also rapidly drying (e.g., Amu Darya and Syr Darya rivers). These changes are attributed to both climatic and anthropogenic factors. Moreover, changes in water resources and their hysteretic effects will have a significant impact on regional climate changes and human wellbeing.

The general topography of Central Asia presents the pattern of east high and west low. Nearly 98.00% of the river discharge origins from the mountainous areas in the eastern parts (Yu et al., 2019). The Tianshan Mountains and Pamir Mountains are the freshwater towers of Central Asia. Glacier and snowmelt water are major suppliers of seasonal rivers, which generally exhibit high fluctuations and a decreasing trend from upstream to downstream. Studies have demonstrated a significant indication of glacier retreat in the eastern mountains (Sorg et al., 2012; Duethmann et al., 2014), which most likely can exacerbate water shortage in vast areas of Central Asia in the following decades. Within the mountains are valleys (such as the Fergana Valley and Alay Valley) and rivers (such as the Amu Darya River and Syr Darya River). Deserts include the Karakum Desert and Kyzylkum Desert. Great lakes include the Aral Sea, Lake Balkhash, and Lake Issyk-Kul. The great lakes in Central Asia are mainly supplied by rivers originating from the mountains, with high evaporation losses during long-distance transport.

Human influences on the environment include greenhouse emissions, land-use changes, pollution, water consumption and management, and other impacts on biodiversity, forests, dust, etc. Summarizing all the anthropogenic effects on the environment in a single study is difficult; however, several studies have investigated different aspects of human influences and presented both positive and negative effects (Yin et al., 2016; Jiang et al., 2017; Gutman et al., 2020). Central Asia is strongly affected by human activities, and unprecedented changes have also deeply affected the environment, such as land use, water, and crops (Sokolik et al., 2020). More research findings and ecological protection will be realized as public awareness of environmental issues increases. However, owing to the stress of population growth and water shortage, there are uncertainties regarding the actualization of land degradation neutrality by 2030 in Central Asia. Currently, it must be guaranteed that major efforts are undertaken for environmental sustainability. The vulnerability and sensitivity of the ecosystem is the practical significance of several studies and discussions being conducted in this region.

2 Climate changes in Central Asia

With increasing global warming, the climate of Central Asia has changed rapidly. Extensive

studies on climate changes in Central Asia have revealed that the region has experienced a rapid warming trend in the 20th century. The average temperature rise in this region is considerably higher than the global average, particularly since the 1960s (Mannig et al., 2013; Hu et al., 2014; Huang et al., 2017). In the last five decades, the average temperature in Central Asia has increased significantly, particularly since the 1980s (Chen et al., 2011). The annual mean temperature has increased at an average rate of 0.30°C per decade from the 1960s to the 2000s based on instrumental data obtained from more than 300 meteorological stations (Yu et al., 2020). The data also indicate a continuous temperature rise in the 21st century (Fig. 1). This warming trend is expected to increase substantially in the future, with more extreme climate events. In terms of spatial distribution, the warming range in northern Central Asia was greater than that in southern Central Asia and the total area with significant warming has increased considerably (Botterill and Hayes, 2012; Li et al., 2015). Generally, Central Asia is becoming warmer; this warming trend significantly affects glacier retreat, which will certainly induce water shortage and very likely intensify water and ecological crises in the 21st century.

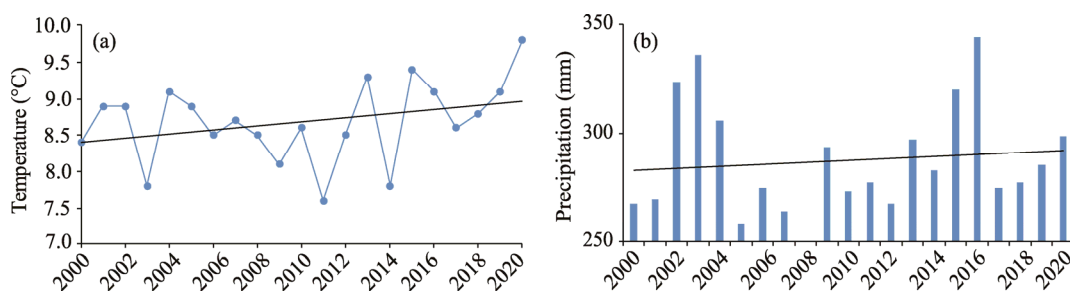


Fig. 1 Annual average temperature (a) and precipitation (b) in Central Asia during 2000–2020

Precipitation, along with surface temperature, is a basic meteorological and climate variable. Variations in precipitation directly or indirectly affect the water–energy exchange among the atmosphere, biosphere, and lithosphere, thereby controlling freshwater supply, food production, disease outbreaks, floods, and droughts (Yatagai et al., 2012; Hu et al., 2016). In Central Asia, precipitation differs considerably from the eastern mountainous regions (more than 1000.0 mm/a (Yang and Du, 2013; Donat et al., 2016) to the vast plain in the middle and northern areas (200.0–400.0 mm/a) and then to the western arid basins (below 100.0 mm/a). The overall precipitation in Central Asia showed an increasing trend of 6.6 mm/decade from 1901 to 2013, and the regional annual precipitation exhibited multidecadal variations (Hu et al., 2017). Generally, the increase in precipitation was higher in mountainous regions than in plain and basin regions. In recent decades, precipitation has increased by 6.9 mm per decade (Fig. 1). The increase in summer precipitation in arid Central Asia was related to the weakening of the East Asian summer monsoon (Chen et al., 2020). Additionally, the effect of human activities on the increase in summer precipitation in Central Asia was noticeable during 1961–2013 (Peng et al., 2018). In most regions of Central Asia, precipitation was increasing not only in summer (mainly owing to rainfall) but also in winter (in the form of snow) (Song et al., 2016). Generally, Central Asia has been wetter in the past century.

3 Socioeconomic development in Central Asia

Statistical data have revealed that the population of Central Asia was growing gradually and its economy was increasing steadily (Fig. 2). Although the area of cotton and other cultivations increased significantly from the 1960s to the 1990s (Yu et al., 2019), the total agricultural land has not been expended in the past two decades. Crop production has also remained stable based on statistical data. Thus, it is nearly impossible to blame agriculture extension for water and ecological crises such as the shrinkage of the Aral Sea in the 21st century. Unbalanced regional development and water interception/transfer have caused the irrational exploitation of water

resources in some watersheds, leading to downstream water and ecological crises. This phenomenon is typical in arid river basins (such as the Tarim River Basin in Northwest China; Yu et al., 2017). Effective measures for ecological restoration include unified water resources management and water conservation at the basin-wide scale, which necessitates urgent consensus and uniform actions among stakeholders.

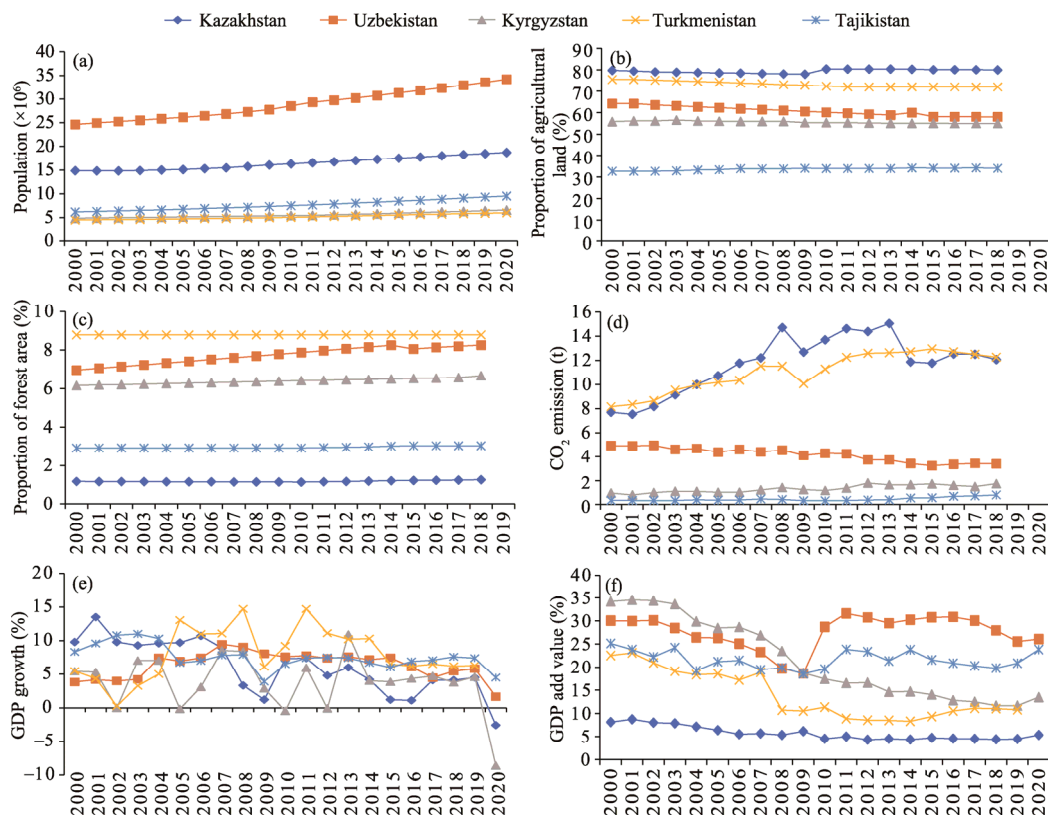


Fig. 2 Socioeconomic development of five Central Asian countries. (a), population; (b), agricultural land; (c), forest area; (d), CO₂ emissions; (e), gross domestic product (GDP) growth; (f), GDP added value of agriculture, forestry, and fishing. Data source: World Bank (<https://data.worldbank.org.cn/>).

Central Asia's population growth has been steady between 2000 and 2020, with annual average rates of 1.30%, 1.94%, 1.73%, 1.68%, and 2.67% in Kazakhstan, Uzbekistan, Kyrgyzstan, Turkmenistan, and Tajikistan, respectively. Thus, Central Asia is a vast territory with a sparse population (less than 19 people/km²), particularly in Kazakhstan (less than 7 people/km²). The total area of agricultural lands (including cultivated land, pasture, garden, fishpond, and all facilities used for agricultural production) has remained stable in Kazakhstan and Tajikistan, with a slight decrease in Uzbekistan, Kyrgyzstan, and Turkmenistan. Forest areas have increased slightly, particularly in Uzbekistan (1.03% annual increment). The increase in CO₂ emissions and gross domestic product (GDP) and the decrease in the GDP added value of agriculture, forestry, and fishing were obvious, indicating the accelerated industrialization and urbanization in Central Asia. Furthermore, to avoid an imbalance between economic development and ecological protection, environmental issues must be given more attention and relevant investment must be increased.

4 Environmental problems in Central Asia

4.1 Water shortage and land degradation

Owing to growing population, agriculture, and industries, the shortage of freshwater has increased

in Central Asia. Current research on water resources in Central Asian countries mainly focused on runoff (Chen et al., 2018), climatic responses (Chen et al., 2017; Kobuliev et al., 2021), and water crisis responses (Zhang et al., 2020). Zhang et al. (2014) reported that the water resource pressure faced by the country increased dramatically with the water footprint of agriculture and animal husbandry in Turkmenistan. Furthermore, they found that the ecological security of water resources became increasingly crucial. To reveal the structure of crop water footprint, Ma et al. (2021) analyzed the spatiotemporal characteristics of crop water footprint in the five Central Asian countries from 1992 to 2017 using crop water footprint assessment method. The results showed that the changes in green water footprint were similar to the variations of cultivation areas, exhibiting an overall decreasing trend; further, the overall blue water footprint also tended to decrease. They also concluded that the green water footprint of crops in Central Asia was mainly from cereals, and the blue water footprint was mainly from cereals and oil crops. Huang and Wang. (2021) calculated the water footprint, water consumption, and the relative state transition probability of the major food crops in the five Central Asian countries based on the methods of CROPWAT model, kernel density estimation, and Markov chain and predicted the relative state transition probability of water consumption by 2042. Their findings showed that wheat is the most water-intensive crop in the five Central Asian countries, with variances in the second-most water-intensive crops in the five countries.

A structural water transfer scheme in Central Asia has been emerging based on remote sensing data and hydrological modeling analysis. There is an increasing water storage trend in northeastern Kazakhstan and a clear decreasing trend in the Aral Sea region. Based on remote sensing analysis, the Aral Sea has been shrinking at an average rate of 1000 km²/a in the past decades. Water resources have generally been transferred from west to east and from the lower reaches to the middle and upper reaches. This water transfer is mainly realized by river closure (reservoirs) and diversion (irrigation) in the upstream. The transferred water is used for regional agricultural and industrial development, resulting in downstream water shortage. Further, it is reasonable to imply that the upstream irrational exploitation of water resources has induced downstream ecological crises, indicating the unsustainable development of Central Asian countries. The consequence of downstream water shortage and ecological degradation cannot be compensated by economic growth. The increase in salt dust, sand dust, and extreme weather will cause long-term damage to human health. The main persistent sources of dust storms originate from the Aral Sea region, north of the Caspian Sea deserts, south of Lake Balkhash, and southern deserts (Indoitou et al., 2012). They are frequent water-scarce regions with sensitive ecosystems. Additional water resources should be diverted to these regions, not away from them.

The water crisis is closely related to land degradation in arid lands. Central Asia has experienced complex land-use changes since the collapse of the Soviet Union, including land abandonment and reclamation (Hamidov et al., 2016). Major land-use changes include the conversion of (1) farmlands to grasslands or urban areas in some regions, (2) grasslands to farmlands or urban areas in some other regions, and (3) waterbodies to grasslands or sparsely vegetated areas. In arid regions, vast grazing areas have degraded owing to climate changes and human activities (Han et al., 2016), particularly in the low reaches of the Amu Darya and Syr Darya river basins (Djanibekov et al., 2018; Zhou et al., 2019). Generally, there have been no significant changes in the total areas of cropland, forestland, and grassland in Central Asia in the 21st century. The most obvious land degradation occurred in the Aral Sea Basin and northern Kazakhstan was caused by regional agricultural reclamation, overgrazing, and water shortage (Han et al., 2018; Li et al., 2019). Soil degradation is also evident in these arid and semi-arid regions owing to intensive tillage, irrigation water mismanagement, and cropping practices (Nurbekov et al., 2016). Reducing crop water stress and improving soil quality remain herculean tasks for local farmers, whereas preventing soil and vegetation degradation are crucial tasks for the governments and other decision-makers.

4.2 Decline of ecosystem services

Ecosystem service is the basis of human survival and development, crucial for the sustainable

development of ecosystems (Costanza et al., 1997; Daily et al., 2000). It serves as a connection between humans and nature, bridging the gap between science and management decisions (Fu et al., 2013). Furthermore, it is instrumental in maintaining the dynamic balance between the Earth's life support system and the environment. Optimizing ecosystem services at the regional scale is a scientific way to achieve regional sustainable development (Fu et al., 2014).

Literature search results have shown that early research on ecosystem services in Central Asia was conducted by Chen et al. (2013). Their research focus was on ecologically vulnerable areas in Central Asia, including land use and land cover changes, net primary productivity, actual evaluation transformation, and crop production. Other recent research group conducted 11 ecosystem service studies in Central Asia. Based on literature review and change analysis (Table 1), the research outcomes indicate that the hotspots of ecosystem services mainly focus on land-use changes (Chen et al., 2013; Shan et al., 2013), value assessment (Li et al., 2019), climate changes (Li et al., 2020), biodiversity (Thevs et al., 2017), tradeoffs and synergies (Mashizi et al., 2019), and scientific research decision-making and management (Saraswat et al., 2015), among others.

Table 1 Ecosystem service studies in Central Asia

Study area	Ecosystem type	Category of ES studies	Methodology/Tool	Reference
Central Asia	Mixed ecosystems	Net primary productivity, actual evapotranspiration, and crop production	Global production efficiency model	Chen et al. (2013)
Kyrgyz Republic	Mixed ecosystems	Provisioning, regulating, supporting, and cultural services	Evaluation method based on money supply, contribution rate analysis, and sensitivity analysis	Shan et al. (2013)
Turkmenistan	Mixed ecosystems	Provisioning, regulating, supporting, and cultural services	Economic valuation	Yao et al. (2014)
Kyrgyz Republic	Mixed ecosystems	Payment of ecosystem services	Economic valuation	Saraswat et al. (2015)
Tajikistan	Forest ecosystem	Provisioning, regulating, habitat, and cultural services	Questionnaire	Mislimshoeva et al. (2016)
Ili Delta	Wetland and catchment ecosystems	Service function of vegetation ecosystem	RapidEye and Landsat satellite images	Thevs et al. (2017)
Central Asia	Mixed ecosystems	Provisioning, regulating, supporting, and cultural services	GIS, CA-Markov model, and IDRISI	Li et al. (2019)
Baghbazm Basin	Semi-arid watershed	Forage production, water yield, carbon stock, soil retention, and soil formation	InVEST and ArcGIS	Mashizi et al. (2019)
Central Asia	Mixed ecosystems	Soil conservation, sand fixation, and net primary productivity	RUSLE, revised wind erosion equation, and CASA	Li et al. (2020)
Central Asia	Mixed ecosystems	Vegetation carbon sequestration, soil conservation, water supply and conservation, and biodiversity conservation	PSO-SOFM	Yan et al. (2021)

Note: ES, ecosystem service; InVEST, Integrated Valuation of Ecosystem Services and Tradeoffs; RUSLE, Revised Universal Soil Equation; CASA, Carnegie-Ames-Stanford Approach; PSO-SOFM, Particle Swarm Optimization-Self-Organizing Feature Map.

According to the study of Li et al. (2019), from 1995 to 2035, the ecosystem service value of waterbodies, croplands, and grasslands accounted for more than 90.00% of the total ecosystem service value in Central Asia. However, from 1995 to 2035, the water area decreased sharply by 38.34%, resulting in a loss of 64.38×10^9 USD. Specifically, from 1995 to 2015, the cropland ecosystem service value increased by approximately 67.89×10^9 USD (Li et al., 2019). The crucial

ecosystem service functions in Central Asia are biodiversity, food production, and water regulation, the ecosystem service value of which accounted for 40.03%, 29.47%, and 10.21%, respectively, in 2015. From 1995 to 2015, the ecosystem service value of water regulation (−12.70%) decreased faster than those of other ecosystem services, followed by gas regulation (−3.00%); the ecosystem service value of cultural, tourism, and biodiversity services decreased by −3.00%, −3.14%, and −0.29%, respectively. The ecosystem service value of grain production, raw materials, climate regulation, soil formation, and waste treatment increased by 4.87%, 7.92%, 12.11%, 12.01%, and 2.91%, respectively (Li et al., 2019).

Spatially, ecosystem service value in Central Asia is usually high in the southeast and low in the northwest, decreasing along the mountain–oasis–desert direction. The ecosystem provisioning, regulating, supporting, and cultural services in Central Asia decreased to varying degrees from 2000 to 2015. The vegetation carbon sequestration and soil conservation areas decreased significantly, accounting for 84.81% and 84.82% of the entire Central Asia, respectively; water supply and conservation and biodiversity protection areas accounted for 69.48% and 19.80%, respectively, which may be closely related to the unreasonable development of regional land resources (Yan et al., 2021).

5 Discussion and conclusions

Central Asia has been warmer and wetter in the past century. Although the climate differs greatly from the mountainous regions to the plain and basin areas, the general trend is now obvious. The annual average temperature and annual precipitation in Central Asia increased by 0.30°C/decade and 6.9 mm/decade in recent years, respectively. Temperature rise significantly affected glacier retreat in the Tianshan Mountains and Pamir Mountains, which may intensify water shortage in the 21st century. The increase in precipitation cannot counterbalance the aggravation of water shortage caused by the temperature rise and human activities in Central Asia. The increase in precipitation in the vast arid regions only increases evapotranspiration, which is difficult to form surface runoff. Furthermore, the upstream water transfer (river closure and diversion) has intensified downstream water shortage, resulting in severe soil erosion and ecological crises. Thus, ecological water must be initially guaranteed in the entire river basins, which require integrated water resources management across the borders of the countries. Typically, ecosystem services in Central Asia are declining, particularly with respect to biodiversity, water, and soil conservation.

Central Asia's population and economy are gradually growing in the 21st century; however, the total agricultural land has not expended. Water interception and transfer resulted in downstream water crises and ecological degradation. In addition, accelerated industrialization and urbanization have intensified this process. Thus, it is the regional overexploitation rather than insufficient total available water resources that shrunk the Aral Sea. There are two perspectives on the recent shrinkage of the Aral Sea. The first one is that there has been a severe ecological crisis in the last 60 years, which has prompted major concerns and criticisms from international scholars. The other perspective is mainly from local experts, who argue that the disappearance of the Aral Sea has a slight impact on animals, plants, and particularly humans in the neighboring villages. However, fully utilizing freshwater resources in the upstream of Amu Darya and Syr Darya rivers has resulted in flourishing agriculture and ecosystems in the oases. Is it a waste of freshwater into the Aral Sea? What will happen if the Aral Sea vanishes? What can we do about this dilemma? To address these questions, we further investigated the ecosystem changes in the Aral Sea region and discovered that most ecosystem services are declining; water-regulated ecosystem service value has declined (−48.07%), followed by recreation, cultural and tourism services (−15.97%), and waste treatment (−15.78%). The value of ecosystem services in the Aral Sea decreased by 40.54×10^9 USD between 1993 and 2018, primarily owing to the rapid decline in the proportion of waterbodies. Considerable loss in the ecological environment in the future is difficult to estimate. The evaluation of such ecosystem services is the first step toward determining the loss owing to environmental degradation and planning future actions. The

ecological degradation in Central Asia is widespread, long term, and detrimental. Thus, trading ecology for the economy is unwise and unsustainable.

Ecological disasters, such as the shrinkage of the Aral Sea, are directly linked to the lack of motivation and cohesive governance by the Central Asian countries. For historical and practical reasons, the parties have so many divergences on cross-border water rights. It is considerably easier to build a dam to separate the waterbody of the Aral Sea than to create a wall to divide the regional climate. Cooperation is admittedly the only way out. From the beginning of the 21st century, a water-ecological monitoring network in the great lakes of Central Asia has been established by the Chinese Academy of Sciences in China and the Central Asian countries. More than 80 real-time monitoring stations were constructed for constant surveillance of water and ecological situations in the watersheds of Central Asia. This network will provide data support for the future optimal allocation of water resources and the sustainable development of the water–ecology–society nexus in the entire region. The water use efficiency in Central Asia is generally low. Further, there is a consensus among most researchers and stakeholders that the development of water-saving irrigation will benefit the entire region. The applications of drip irrigation, seepage control, and other technologies are rapidly developing. Government management and public awareness are also improving rapidly in the 21st century. Additionally, scientific research and local practice must be integrated to better benefit the entire region.

Central Asia has been the link between East Asia and Europe since ancient times. It has now become an important pivotal area along the "Silk Road Economic Belt". The environment and development of this region have always been a major concern to many international organizations, including the Shanghai Cooperation Organization (SCO) and the Alliance of International Science Organizations (ANSO). The coordinated development of society, economy, and environment in Central Asia is the common goal of the five countries and other third parties. As no integrated hydrological and ecological monitoring system has been established in Central Asia, considerable data are imperfect owing to historical reasons, and the relevant research is relatively backward. However, geoscience, economic, and social science studies in Central Asia have recently become popular. A path to sustainable development will ultimately be identified and established with more attention and efforts.

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